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DEVELOPMENT AND EVALUATION OF A LASER ANGULAR RATE SENSOR FOR USE IN SEVERE ENVIRONMENTAL APPLICATIONS (U)

Final Report - Volume I of 3

Michael O. Pekkarinen
Ted J. Podgorski
Honeywell Inc.

November 1968

Nike X Development Office
Redstone Arsenal, Alabama

Contract No. DA-01-021-AMC-14533(Z)

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DEVELOPMENT AND EVALUATION OF A LASER ANGULAR RATE SENSOR FOR USE IN SEVERE ENVIRONMENTAL APPLICATIONS (U)

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FOREWORD

This program was sponsored by the Army Ballistic Missile Defense Agency, Project DEFENDER, per ARPA Order 744. The contract was let by the U.S. Army Missile Command, Redstone Arsenal, Alabama.

Contract No: DA-01-021-AMC-14533(Z)

Contract Date: 1 April 1966

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Credit for substantial contributions to the program accomplishments is given to the following persons, in addition to the authors:

Dr. S. R. Alexander	ABMDA
Mr. Kenneth Blythe	SENSCOM
Mr. W. Gibson	NIKE-X Development Office
Mr. J. V. Johnston	AMICOM
Mr. R. R. LeChevalier	Honeywell

ABSTRACT

This summary volume is Volume I of three volumes which make up the Final Technical report for the Laser Angular Rate Sensor (LARS) program. The program was sponsored by the Advanced Research Projects Agency and was contracted and administered by the Army Missile Command. The purpose of the program was to develop and qualify a rate sensor for anti-ballistic missile applications. Following an extensive developmental phase, two flight-weight LARS units were fabricated and subjected to a thorough range of performance and environmental tests. The environmental tests were extremely severe, taxing the capability of state-of-the-art test facilities. Program results were very encouraging in all aspects. Performance goals were met or exceeded in seven of eight key areas. The reaction time goal was not met, but the technology is now available to provide the very fast reaction time characteristics desired. Environmental goals were met or exceeded in five of the seven major environments. In the two areas -- temperature range and random vibration -- the technology is also now available to meet the program objectives.

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SECTION I
INTRODUCTION

The objective of this program was to develop, fabricate, and test two three-axis Laser Angular Rate Sensor (LARS) packages. These devices shall be capable of providing missile body rate information over the appropriate range of accelerations and rate encountered in Hard Point Defense. The small, lightweight LARS package was to be developed to the point where adequate hardware was available for a complete spectrum of ground qualification tests. These tests were to be conducted to the limit of the technical requirements, if possible, and there v verify the feasibility of the selected design approach.

In selecting the laser gyro as a promising and likely solution to the anti-ballistic missile guidance problem, the program Steering Committee (composed of ARPA and AMICOM personnel and their consultants) was capitalizing on the following basic characteristics of the proposed LARS:

- Gravity insensitivity
- Very high rate capability
- Solid-state construction
  - No moving parts
  - No wearout mechanism
- Simple/rugged configuration
  - High reliability
  - Severe environmental capability
  - Low-cost potential

Since the operation of the laser gyro is dependent entirely on detecting the frequency split of two laser beams in a common cavity, theory predicts that the performance of the basic device will be insensitive to any environmental exposure. The substance of this program was devoted to demonstrating the practicality of the laser gyro concept in a severe environmental application. The relative specified environmental levels -- vibration, shock, and linear acceleration -- are compared in Figure 1.

The brief description of laser gyro principles, discussed in Appendix A, provides a basic understanding of the laser gyro and how the unique characteristic of gravity insensitivity occurs.

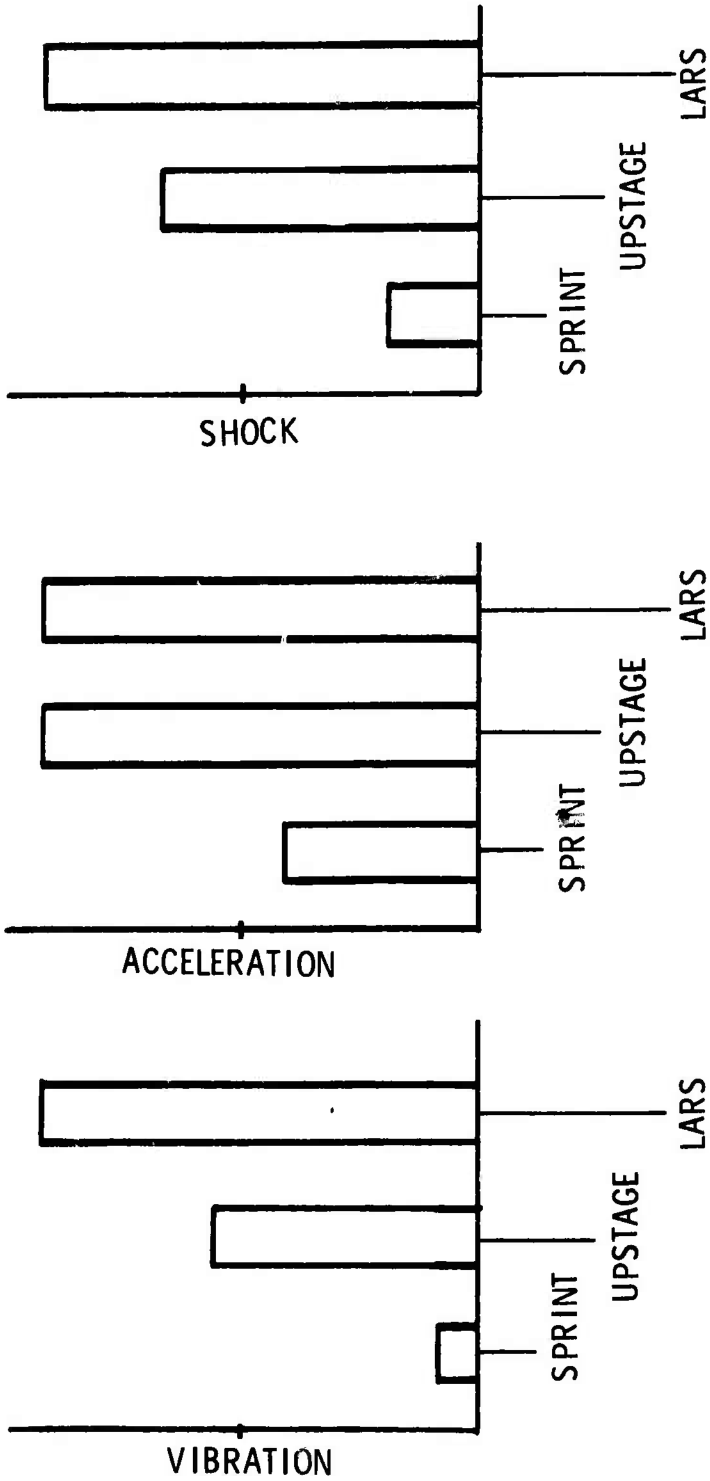

Figure 1. Environmental Comparison

SECTION II
SUMMARY

The program summary plan is shown in Figure 2. The original plan for a two-year program stretched out to 28 months as a result of program problems discussed in this volume. A brief discussion of each of the major program activities is given here.

The Analytical Studies were in two primary areas -- high-g/high rate effects and lock-in compensation techniques. The analysis of possible errors in the laser gyro due to the influence of the high-acceleration and high-rate inputs showed that any such errors are extremely small, less than one part in 10 million (10^7). The compensation technique study investigated the projected characteristics of the current dither technique for overcoming the lock-in, or deadzone, phenomena of the laser gyro. The result of this effort confirmed analytically and experimentally that current dither would indeed overcome lock-in and would permit the projected LARS configuration to meet the rate accuracy requirements.

Subassembly Development was devoted to the design and evaluation of the cathode and anodes for the gas discharge, a reliable and convenient laser pinch-off (sealing) technique, miscellaneous mechanical elements, and the wideband readout amplifier and current dither electronics. Designs were made and implemented in breadboard-type hardware and evaluated, where appropriate, in the various environments to confirm basic integrity of the planned configurations prior to fabrication of the two program units.

Structural Development covered the analysis, fabrication and test of the mechanical mounting for the quartz sphere, which contains the three ring lasers. During this phase dummy loads were tested in actual and simulated environments to confirm the adequacy of the sphere mounting configuration. This was successfully accomplished prior to triad build.

The single-axis gyro was built and tested early in the program to provide confirmation of the basic LARS design. Tests were made of the functional performance, and limited environmental testing was also carried out. Linear acceleration tests to 165 g's, the limit of Honeywell's in-house capability, were performed successfully with no indication of g sensitivity.

Following Steering Committee approval of the triad design, the LARS unit was fabricated for the test phase. Each unit contained the quartz sphere with three ring lasers, a mounting frame, readout amplifiers, connectors, and covers. Each test phase included a complete functional evaluation in addition to a series of rigorous environmental exposures. In general, the

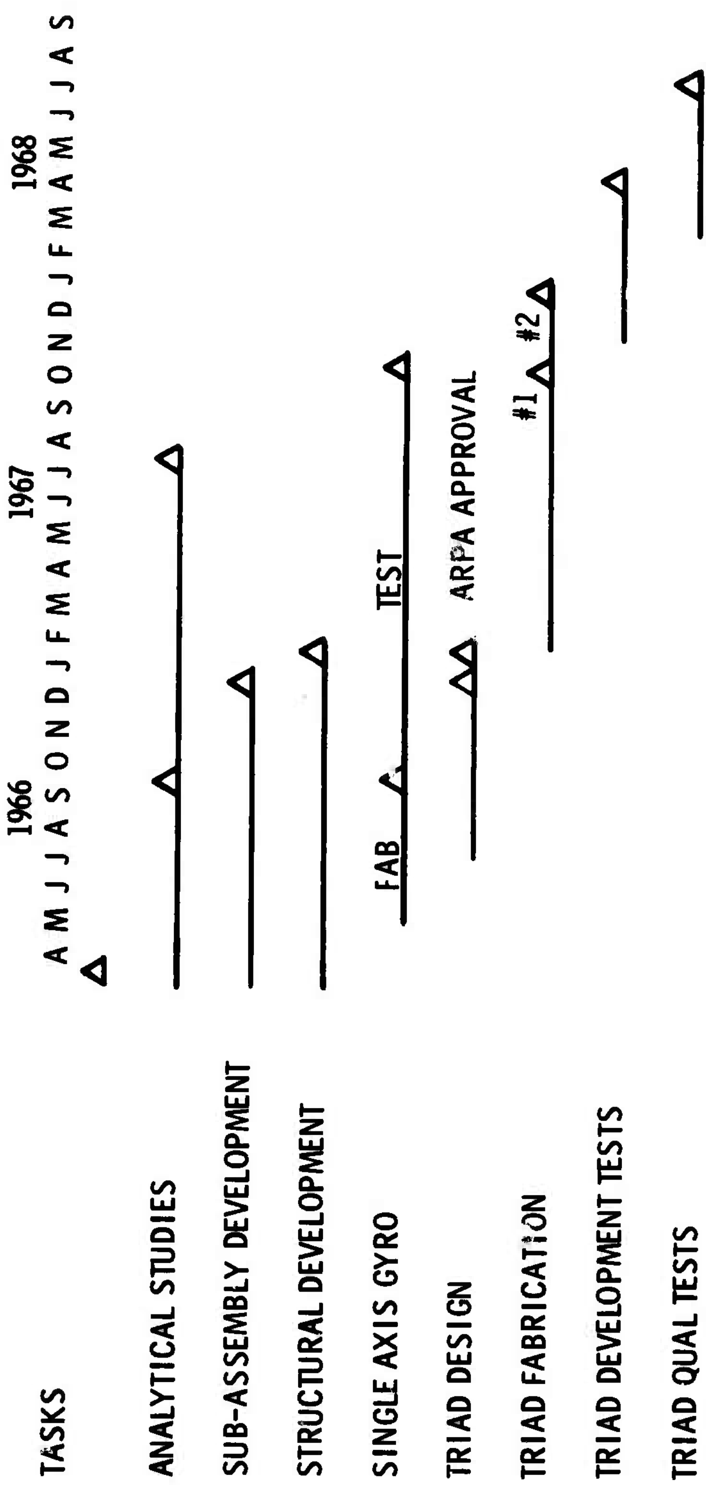

Figure 2. LARS Schedule Summary

results of the test phase were very encouraging. Program objectives were met or exceeded in seven of eight key performance areas and five of seven environmental areas, as shown in Tables 1 and 2.

(C) Table 1. LARS Objectives Accomplishments - Performance (U)

Performance Item	Objective	Accomplishments
Scale Factor	$>2^{10}$ pulses/radian	$4/5 \times 2^{16}$ p/rad
Error Band	±0.5°/sec or ±0.5%	±0.32°/sec ±0.05%
Threshold	0.1°/sec	<0.1°/sec
Null Offset	<0.05°/sec	≈0.05°/sec
Frequency Response	>75 Hz	>100 Hz
Reaction Time	1 sec	<1 sec after stabilization
Lifetime	600 hours	>1,000 hours
Max. Input Rate	600°/sec	600°/sec

(C) Table 2. LARS Objectives Accomplishments - Environmental (U)

Environmental Item	Objective	Accomplishments
Linear Acceleration	400 g	Same
Shock	600 g	800 g
Random Vibration	20 g^2/Hz	Marginal
Angular Acceleration	500 rad/sec^2	Same
Thermal Ambient		
Operating	+40 to +175°F	Thermal control required
Nonoperating	-65 to +175°F	Marginal
Acoustic Noise	165 db	Same
Altitude	100,000 ft	Same

SECTION III

LARS CONFIGURATION

(U) The LARS package consists of a laser gyro triad and associated readout amplifiers. The power supplies, digital output, and dither electronics were left outboard in the interest of program economy (Figure 3). The physical characteristics of the resulting three-axis package are compared to AGENA and SPRINT packages in Figure 4. A cutaway of the LARS is shown in Figure 5.

(U) The design configuration of the LARS features three orthogonal gas ring lasers of triangular shape machined into a solid quartz sphere. Nine dielectric mirrors molecularly bonded to the surface of the sphere both seal the cavity and form the reflecting corners of the laser paths (Figure 6). The six helium-neon discharges that provide pumping power for the lasers have separate anodes, but share a common cathode. This discharge configuration, shown schematically in Figure 7, had never been attempted previous to the LARS design and its success provided one of the key elements in the current dither form of lock-in compensation.

(U) The current dither lock-in compensation method featured in LARS takes advantage of the capability of flowing gas ions to produce a frequency split between the two laser beams. As a result, the locking of the two beams is overcome, permitting the LARS to sense low input rates.

(C) Adaption of the quartz sphere configuration to an airframe interface presents a challenging design problem. The final configuration consisted of an invar mounting ring which was located at the equator of the sphere. The ring had three clamping surfaces 120 degrees apart which are clamped onto three sets of flats machined into the sphere. A cross section of the clamp design is shown in Figure 7. A thermal match between the mounting ring and quartz ball was maintained by means of a compensating shim, which permitted temperature extremes of -65°F to 175°F. The readout amplifiers were packaged using thick-film technology and were mounted directly to the invar ring with brackets. Photographs of the LARS with and without covers are presented in Figures 9 and 10.

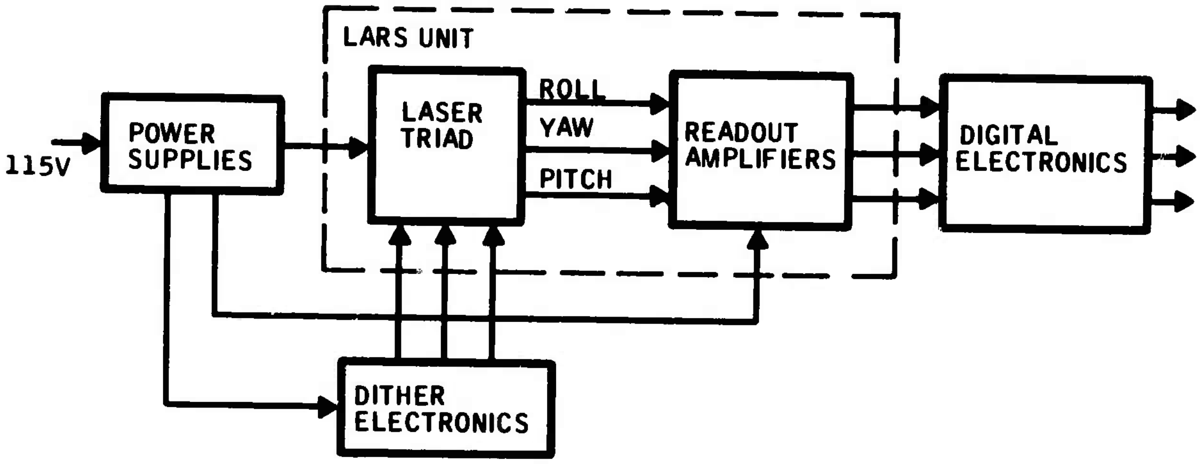

Figure 3. LARS Block Diagram

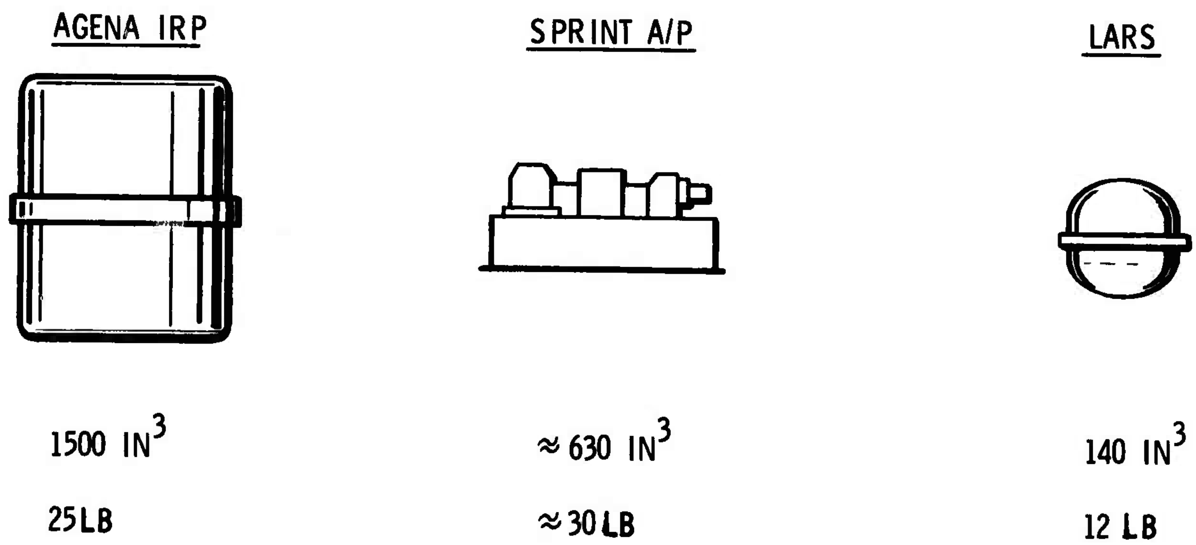

Figure 4. AGENA, SPRINT, LARS Size Relationships

Figure 5. Cutaway of LARS

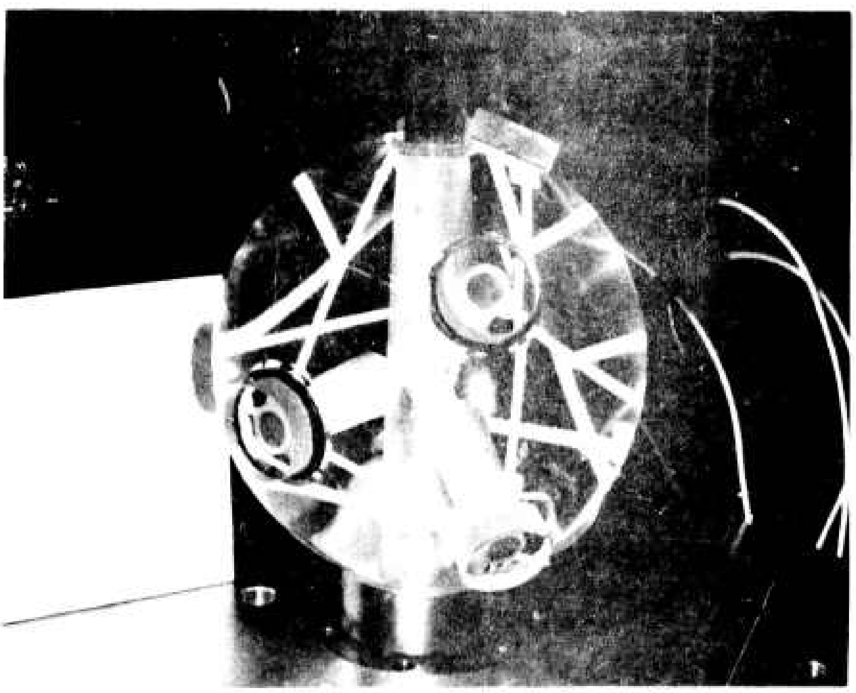

Figure 6. LARS on Fill Station

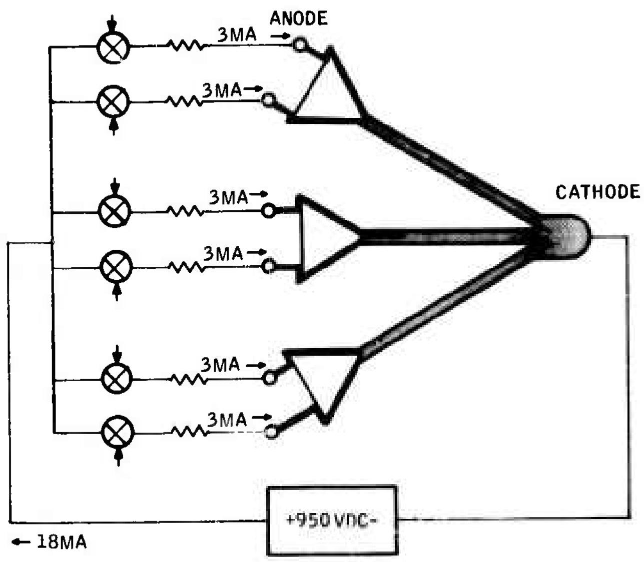

Figure 7. LARS Excitation

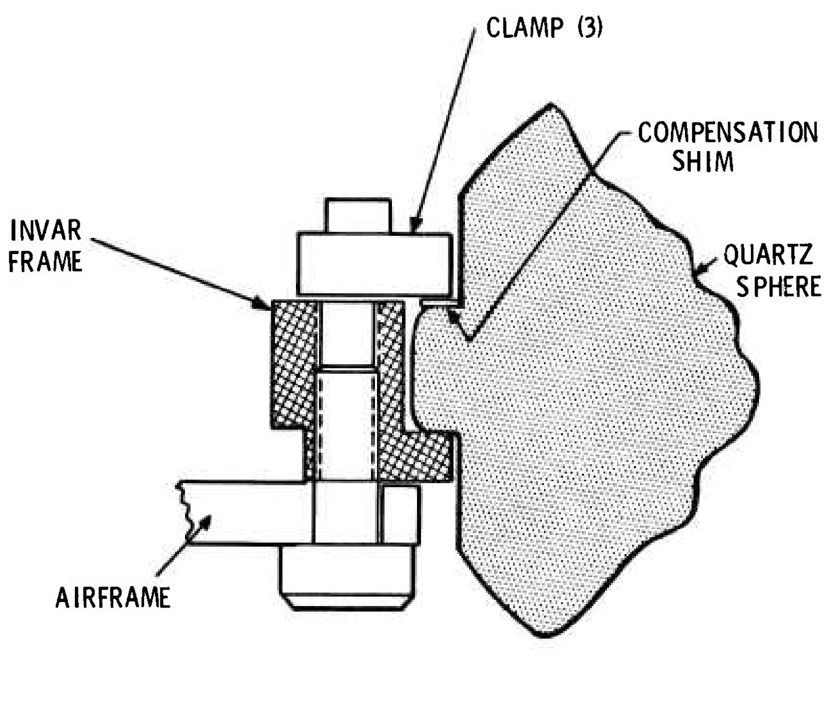

Figure 8. LARS Mounting Detail

Figure 9. Completed LARS Assembly

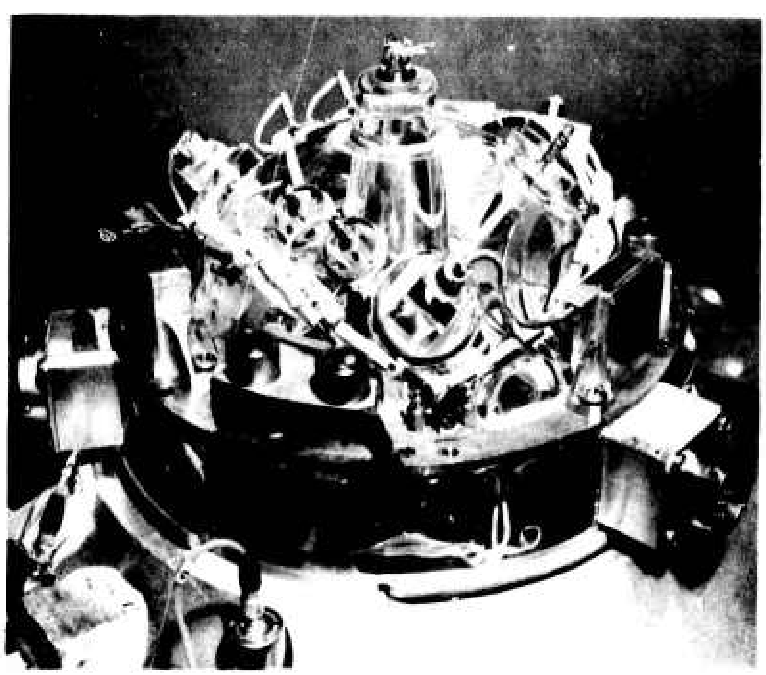

Figure 10. LARS With Top Cover Removed

SECTION IV
PROGRAM GOALS - ACCOMPLISHMENTS

(U) The accomplishments of the LARS design are compared to specific design objectives in Tables 1 and 2. The objective column represents the requirements as defined in Technical Requirements 819, (TR819) dated February 1966. Comments concerning the accomplishment column follow.

LABORATORY PERFORMANCE

Scale Factor

(C) The scale factor of the LARS gyros is directly proportional to the area enclosed by the lasing triangle. A design goal of 0.8×2^{16} pulses per radian (nominal) was established to be consistent with the LARS size. The variation in scale factor from assembly to assembly was ± 0.4 percent from nominal. The scale factors of the three gyros in a given assembly were within 0.05 percent of each other. The 0.47 percent variation from nominal is an indication of gaging deficiencies which must be overcome if precise nominal scale factors are to be achieved on a high yield basis.

Error Band

(C) TR819 specified an envelope of limits bounded by ±0.5 deg/sec or ±0.5 percent of ideal under all conditions and environments. The overall performance of the LARS against that goal is ±0.32 deg/sec, ±0.05 percent. The major contribution to that value can be divided into two performance areas - laboratory and environmental. Under laboratory performance, three terms are significant.

Rate linearity 0.22 deg/sec	RSS of rate data deviation from ideal transfer over full input range of LARS
Scale Factor stability 0.03%	Two terms represent stability of ideal input-output transfer function.
Null stability 0.04 deg/sec	

(C) In addition to the laboratory performance, the following environmentally induced error contributions will be considered:

Linear acceleration	0.02 percent	Total error band over 275g
Angular acceleration	0.02 deg/sec	Peak error at 500 rad/sec^2
Vibration	0.04 deg/sec	Peak error at 30g

(C) Environmental performance information was restricted to the above three environments because of environmental test facility limitations with respect to alignment and stability. Even then, the environmental error terms are probably more indicative of test facility limitations than a change in LARS performance.

Threshold

(C) TR819 specified a threshold requirement of 0.1 deg/sec, where threshold is defined as the minimum input rate which produces a change in output. The LARS unit, with the current dither compensation, has a continuous input-output relationship, thereby satisfying the threshold requirement.

Null Offset

(C) The null offset requirement for the LARS was specified to be ±0.05 deg/sec. For a symmetrical discharge design such as in the LARS, the intrinsic null offset is quite low. The small offset percent can be readily trimmed by unbalancing the d-c component of the discharge current such that the resulting net gas flow opposes and cancels the null offset. The measured value of the LARS, as trimmed, was 0.03 deg/sec. This relatively high value is not indicative of the trim capability, but reveals a calibration procedure deficiency. Null offset on succeeding units can be controlled more accurately.

Frequency Response

(C) The laser gyro, with its solid-state construction, has no known upper frequency limit. The LARS device was tested at input frequencies up to 100 cycles, the test facility limit. Predictably, the LARS performance remained unchanged at all frequencies.

Reaction Time

(C) The reaction time goal specified by TR819 for the LARS was one second. Since the starting mechanism of the LARS consists of charging a capacitor and discharging it through a transformer, the inherent starting capability of the LARS would be on the order of 100 milliseconds. However, as the development of the LARS proceeded, it became apparent that the effectiveness of the current dither compensation was a function of the optical path length. At that point in the laser gyro development process, the most straight-forward approach to maintaining optical path length - temperature control - was selected. Because of the long thermal time constants associated with the LARS hardware configuration, it was found that a 2-hour stabilization time was now required. In future systems, this stabilization time can be eliminated by the

(C) use of an active, closed-loop-length control transducer which will control optical path length independent of temperature.

Lifetime

(C) The lifetime goal specified by TR819 was 600 hours operating time, and 1-year shelf storage. This requirement was an area which required extensive development throughout the program and culminated with a demonstration of operating life in excess of 1000 hours. This success came quite late in the program, making it impossible to demonstrate the shelf life withinthe program constraint. However, based on experience obtained from other Honeywell laser gyro programs where 1-year shelf life has been demonstrated, no problem in attaining that goal using LARS hardware is anticipated.

Input Rate

(C) The input rate range of 0. 1 deg/sec to600 deg/sec is a key requirement in an ABM-type sensor. While the laser gyro approach is theoretically capable of measuring rates up to 30, 000 deg/sec, a practical limitation is presented by the bandwidth requirement of the detector-amplifier combination. The LARS design demonstrated the capability of sensing input rates to 600 deg/sec using a silicon photodetector and a thick-film amplifier design. This was an area which required extensive design development during the course of the program and one which is continuing to receive Honeywell support. Current development has demonstrated rate detection to 2000 deg/sec.

ENVIRONMENTAL PERFORMANCE ACCOMPLISHMENTS

Linear Acceleration

(C) TR819 specified operation in a linear acceleration environment of 400g's along the longitudinal axis and 300g's in any plane normal to the longitudinal axis. The LARS was subjected to an acceleration of 416 g's in each of two orientations on the centrifuge located at MDAC-WD in Santa Monica. Two LARS assemblies were subjected to a total of 12 exposures at the full g level. Both units were operated throughout the exposure and provided continuous output information. Accuracy limitation of the centrifuge facility masked the performance of the LARS, so additional testing was conducted on a more accurate machine to the 275-g level. This second test verified the performance stability of the LARS to be better than 0. 05 percent under 275 g stress levels.

Shock

(C) TR819 specified operation in a 600 g, 2.5 millisecond, half sine shock environment. This loading was applied in each of four orientations for a total of 12 exposures. On several occasions the peak level actually exceeded 800 g's. The LARS assembly operated throughout the exposure and provided continuous output information.

Random Vibration

(C) TR819 specified a random vibration spectrum of $20 g^2$ per cps. from 200 to 2000 cps. This level exceeds the capability of all vibration test equipment currently available in the United States. In order to be responsive to the requirement, two different vibration simulation techniques were employed. The first simulation technique used is commonly referred to as a split spectrum approach. In this approach, the total frequency bandwidth was split into 100 cps increments and the $20g^2$ energy level applied over that bandwidth. The LARS assembly successfully passed this test in two orientations.

(C) The second simulation technique used is called a swept random approach. This approach consists of exposing the device to the desired random spectrum sequentially by sweeping the spectrum with a 10 cps bandwidth filter. The LARS assembly survived four exposures at $10g^2$/cps before failing catastrophically. The two simulation techniques provide significantly different inputs, neither of which conforms to the requirement. The presence of conflicting test results serves to flag a specification requirement which should be examined and, if found really needed, specified more thoroughly on future programs.

Sinusoidal Vibration

(C) TR819 specified a sinusoidal vibration spectrum of 5 to 27 cps at 0.20 inch double amplitude to 7 g's, 27 to 200 cps at constant energy, 200 to 400 cps with energy increasing at constant displacement from 7 g's to 30 g's, 400 to 1500 cps with constant acceleration of 30 g's. The LARS was subjected to this input while in an operational mode and revealed no change in output characteristics.

Angular Acceleration

(C) TR819 specified operation in a 500 rad/sec squared angular acceleration environment at frequencies up to 75 cps. The LARS was tested at levels and frequencies up to 500 rad/sec^2 and 100 cycles with no change in device performance characteristics. Performance stability of the LARS during the

(C) exposure was ±0.02 deg/sec, well within the specified requirements.

Thermal Ambient

(C) TR819 specified a survival temperature range of -65°F to 175°F and an operating temperature range of 40°F to 175°F. During the development phase, LARS-configured hardware successfully withstood the survival temperature range as specified. However, as the development of the current dither compensation progressed, temperature control was employed to maintain dimensional stability in order to enhance the compensation effectiveness. The temperature control configuration included the addition of a heat-conducting epoxy to the space between the quartz sphere and the mounting ring. With this epoxy in place, additional hoop stresses were inflicted on the quartz sphere in the low-temperature environment. This configuration was found to be unacceptable at -65°F and is one area in need of further development.

(C) The operating temperature range requirement was also affected by the temperature control decision. Although there is no inherent reason that would limit operating of a laser gyro in the temperature range of 40 °F to 175°F, the selection of the temperature control point at 116°F for the LARS configuration limited its ambient temperature range to temperatures below 116°F.

Acoustic Noise

(C) TR819 specified operation in a 165db acoustic noise environment. The LARS was successfully operated under these conditions and revealed no harmful effects.

Altitude

(C) TR819 specified operation at altitudes up to and including 100,000 feet above sea level. The LARS was successfully operated under these conditions for over 4 hours with no harmful effects or change in performance while operating in that environment.

SECTION V
MAJOR DEVELOPMENTAL TASKS

When Honeywell began work upon the LARS development, our experience consisted of fabricating and testing single-axis, solid-block ring laser gyros similar to the one shown in Figure 11. These devices were basically laboratory units which aptly demonstrated the feasibility of undertaking a task as complex as the LARS development, yet left unanswered many important and complex questions. Every aspect of the then current design had to be rethought, reevaluated and, in many cases, redesigned in the face of the LARS requirements. Numerous problem areas arose, and often, a second, and larger problem, seemed to replace each resolved problem. In retrospect however, all difficulties seem to fit into three broad categories:

- Cavity and lock-in compensation development
- LARS lifetime development
- Structural and environment development.

CAVITY AND LOCK-IN COMPENSATION DEVELOPMENT

The fact that these two rather complex topics are handled as one indicates the complexity of the problem which had to be overcome in this program. The two topics became inseparable early in the program when the decision was made to employ current dither as the form of lock-in compensation to be used on LARS.

The current dither from of lock-in compensation depends on generating a frequency splitting of the two lasers by means of a differential gas flow between the two discharge legs. The frequency split can be optimized two ways - by increasing the gas flow and/or by increasing the laser gain which changes the index of refraction with the cavity. Unfortunately these two phenomenas are not independent and a tradeoff was made to optimize the current dither effect in light of these two considerations.

Considered independently, the optimization of current dither by adjusting the gas flow and gain parameters is not particularly difficult. However, it is not possible to consider them independently because of requirements placed on the:

- Minimum signal output
- Single-mode operation
- Single-polarization operation

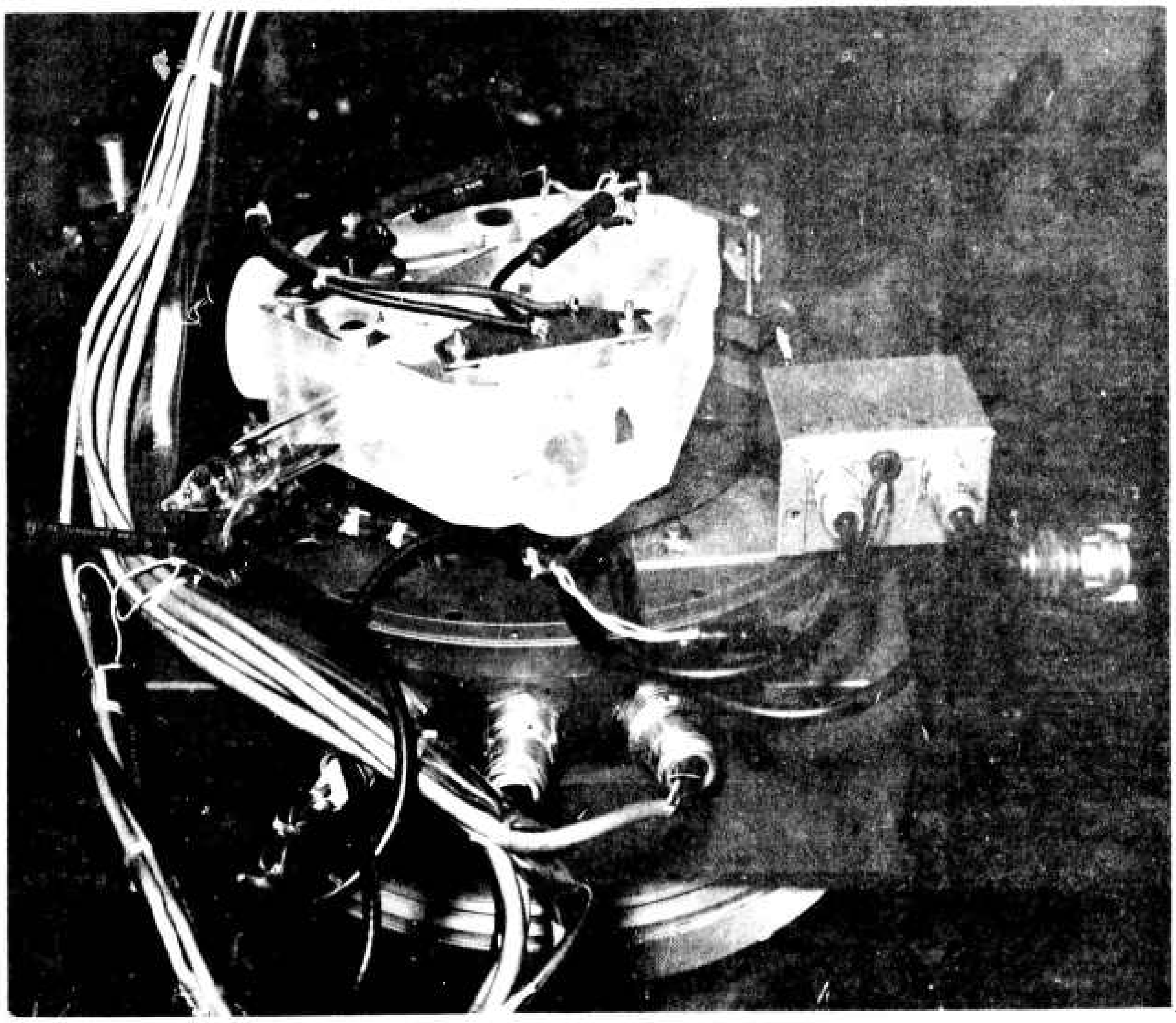

Figure 11. Early Research Gyro

- All-temperature operation
- Mode-pulling effect on scale factor
- Lifetime requirements
- Power requirements.

When go-ahead on the LARS contract was given, the performance of ring lasers over the full doppler broadened gain curve was not well defined. As the theoretical work progressed and the complexity of the task emerged, it appeared evident that a series of experiments aimed at generating design curves would help to bracket the problem. A unique experiment was contrived which allowed ring laser performance to be measured for 14 different combinations of gain and gas flow (see Figure 12). This experiment generated data which defined the physical restraints of the LARS and triggered decisions which defined specific design problems which could be approached and solved individually. The net result was the LARS unit which satisfactorily met all of the requirements except for the all-temperature operation. Equally important, however, the knowledge gained makes possible future design modifications and optimization to fit an entire spectrum of applications.

LARS LIFETIME DEVELOPMENT

At the time of contract award, Honeywell had built and tested ring lasers with a demonstrated lifetime capability in excess of 600 hours operating, and one year shelf storage. This had been achieved using techniques and materials which were not entirely compatible with the rigorous environmental requirements and the low pressure-high cathode current density of the LARS. Extending gas laser technology into these unknown areas proved to be a long and difficult task.

The lifetime capability of a d-c discharge system is centered around two basic considerations:

- The selection and procession of a cathode material which will not remove substantial quantities of He-Ne from the medium (no gas clean-up).
- The ability to enclose the gain medium (HE-Ne gas at 2 to 8 torr) in a cavity and maintain a gas impurity level to 0.01 to 0.05 torr during exposure to severe environments.

The gas clean-up phenomena was not a serious hurdle in achieving the LARS lifetime requirement, partially because the 600-hour operating life is not a difficult requirement in terms of clean-up. In addition, the subject of cathode selection versus clean-up has been treated frequently in the literature. That literature, combined with previous experience, led to a cathode

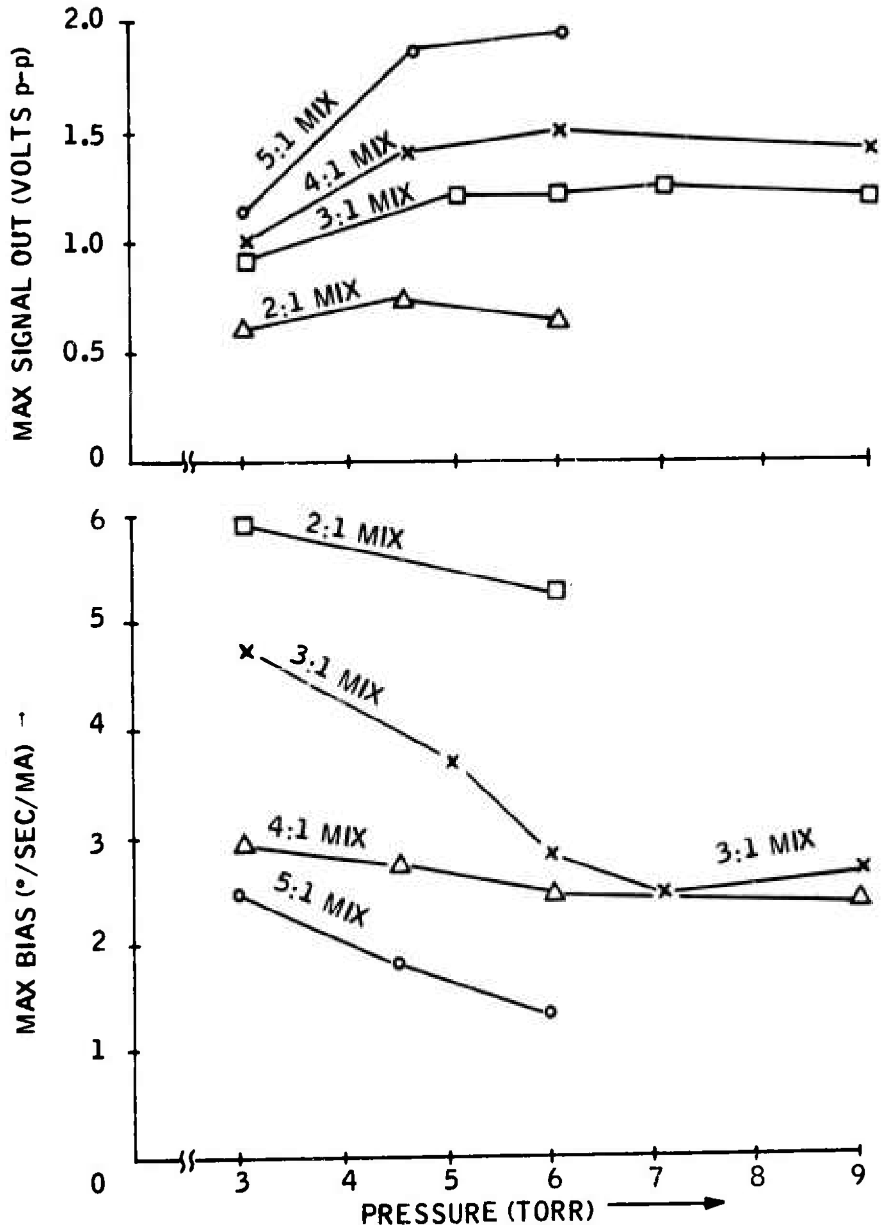

Figure 12. Bias and Signal Sensitivity versus Pressure

design early in the program which gave no serious clean-up problem.

The second consideration - the ability to maintain a high purity gas mixture - is dependent upon the seal effectiveness and the cavity's material cleanliness and outgassing properties. The most pertinent issue, and the essence of the problem that had to be overcome, was Honeywell's ability to qualitively measure the effectiveness of the sealing and material selection. This involved obtaining the measuring capability that could detect gas impurities of 0.01 to 0.05 torr in an operating ring laser. Once this measuring capability was established, a series of comparison tests which qualitatively evaluated the effect of material selection, seal effectiveness, and assembly techniques led to the selection of materials and processes consistent with the LARS lifetime goals. The achievement of the lifetime requirement was demonstrated with a 1000+ hour test using program hardware. If significantly longer life is required, continued development work utilizing present measuring techniques should yield fruitful results.

STRUCTURAL AND ENVIRONMENTAL DEVELOPMENT

The task of adapting the laser gyro to survive very high-g environments presented a challenging structural problem. In addition to the need for maintaining alignment of the laser components and of the gyro axes, the structural integrity of the triad supporting structure had to be considered. The major contribution toward meeting the severe g requirements was the use of a quartz sphere to house the three laser planes. The rigidity and low thermal expansion of the quartz sphere provided an excellent basis for a stable structure. Considerable development effort was expended in designing a supporting structure for the sphere and its electronics which was compatible with the environmental requirements. Although this was a difficult task, it was successfully completed relatively early in the program.

The early achievment of this goal preceded the design finalization by 6 months and this time element is a factor in any structural deficiency which appeared later in the program. As the development on the triad assembly proceeded, changes in the design and test procedures occurred. While these changes were reviewed in the light of the structural development work, no hardware evaluation was conducted. Analysis of the failure after the fact indicated that continued development, supported by hardware evaluation in the areas that were changed, would have avoided the failures. The lesson to be learned from this experience is that when working at extremely high stress levels, particularly with brittle materials such as quartz, calculation and design concepts must be confirmed empirically to ensure success.

SECTION VI
RECOMMENDATIONS FOR FUTURE RESEARCH AND DEVELOPMENT

(C) The present program has demonstrated the feasibility of the laser gyro approach for ABM applications. Demonstration of the performance goals in both the lab and severe environments was highly successful. However, two items specified in Technical Requirements 819 were not accomplished - the 1 second ready time and the structural integrity in 20 g^2/cps vibration environment. Based on present technology, the vibration structural integrity is a straight-forward development task which should probably be delayed to fit a specific application. Therefore, areas of research and development which are candidates for immediate attention fall into three general categories:

- Advancement of LARS performance
- Reduction of LARS operational ready time
- Significant physical reduction.

REDUCTION OF OPERATIONAL READY TIME

(C) LARS performance is dependent upon certain gain considerations which vary as the optical path length changes. Cavity length variation caused by temperature shifts due to ambient changes and device warm-up currently effect LARS performance to the extent that a 2-hour stabilization time is required. Ready time is a consequence of the gyro housing material used and the form of cavity length control employed. In the LARS design standard fused quartz having a coefficient of expansion of 9×10^{-7} in/in/°F was used. This coefficient with the LARS geometry caused the gain terms of the gyro to have a 13°F cycle. This gain instability was overcome on the LARS by temperature controlling the gyro housing to a fixed temperature at the expense of long ready times.

(U) A more attractive alternative now feasible and directly applicable to the LARS design includes changing the block material to Corning's Ultra Low Expansion (ULE) fused quartz and implementing closed loop piezoelectric length control. The expansion coefficient of ULE quartz over the temperature range of interest is 0.4×10^{-7} in/in/°F. For this material, the gain term will cycle only once over a 330°F range. This implies minimal length changes which can readily be controlled using present piezoelectric length control design technology. The net result of this change would be a LARS ready time of less than one second, plus increased scale factor stability.

ADVANCEMENT OF LARS PERFORMANCE

(C) The low rate (below 20 deg/sec) performance of the LARS is dependent on the effectiveness of the current dither compensation. At the present state of development, peak errors in that range are on the order of 0.5 deg/sec. Accuracy is entirely dependent on the dither capability which can be attained through gas flow versus the magnitude of the natural lock-in. Therefore, performance improvements of the LARS are tied to development in the two areas:

- Lock-in reduction
- Dither (bias) improvement.

Lock-In Reduction

(U) The multi-layer dielectric mirrors used on the present LARS are state of the art and have scattering in the range 0.001 - 0.005 percent. Significant improvement in this area cannot be expected in the near future. The mirror scattering is such that other lock-in terms are now very important and work in these areas is expected to be much more fruitful. Even though the mirror scattering determines the average value of lock-in, the gain medium itself plays an extremely important role in determining lock-in as a function of operating point on the gain curve. Internally funded work and data taken on other contracts has indicated that lock-in is not a random function, but depends on the properties of the gain medium. If, after experimentally determining how lock-in varies as a function of gain, mirror reflectivity, operating point on the doppler curve and pressure, and this behavior can be explained in terms of the Aronowitz model of the ring laser, significant reduction in lock-in threshold will be possible.

Dither (Bias) Improvement

(U) The dither compensation presently employed on LARS utilized differential mode pulling due to moving gain atoms within the cavity. Further research aimed at enhancing this effect is attractive:

- Investigating the feasibility of taking advantage of the lifetime breakthrough and improved readout capability recently achieved on the LARS program to increase the Langmuir flow of the gas by operating at reduced pressure and a lower He:Ne ratio and lower output power.

- Investigating the feasibility of using a flat linear indiction pump (FLIP) for inducing motion of the gain atoms.

With the recent breakthrough in LARS triad lifetime it now appears feasible to increase the current bias by a factor of 3 or more by operating at lower pressure with a lower ratio of He and Ne using a larger discharge current differential and still maintain a 1000 hours or more of operational lifetime (Figure 12). To verify this, additional lifetime work will be necessary. Also, some effort will have to be spent on the readout system to eliminate the effects of power output modulation when full advantage is taken of the current differential possible in the two legs of the gyro.

The FLIP is the linear analog of the conventional rotating induction motor. The rotor in an induction motor is a squirrel cage of conducting bars which rotates under the action of a rotating magnetomotive force. In a linear induction motor the "rotor" simply becomes a conducting bar which translates under the action of a traveling magnetomotive force. The translator may be a conducting fluid like the plasma in a laser discharge tube. In this case the linear induction motor acts as a gas pump.

A FLIP normally consists of a set of graded windings on a laminated iron core. It has no moving parts and it appears that it might be possible to eliminate the iron core structure. It can be applied over the discharge tube by properly machining the gyro housing. Nothing needs to be added into the gyro cavity and the pump itself can be controlled independently from the laser. Feasibility could be determined using commercially available motors. An order of magnitude increase in the bias level appears possible.

SIZE REDUCTION

At the present state of technology the basic solid-block construction laser gyro appears to be quite adaptable to a significant reduction in size and weight. It appears technically feasible to scale down the LARS optical cavity by as much as a factor of 3 and maintain high-g capability and performance. This design would depart radically from the LARS concept, but looks extremely attractive for applications 2 years away.

APPENDIX A
LASER GYRO PRINCIPLES

INTRODUCTION

The principles of laser gyro operation were established many years ago by Albert Michelson. Michelson and Gale measured the rotation of the earth in 1925 by taking the light from a carbon arc source and splitting it into two beams. The scientists passed one beam in a clockwise direction and the other in a counterclockwise direction within a large enclosed rectangle. (This area measured 2010 feet by 1113 feet and was constructed from 12-inch sewer pipe.) The two beams were then mixed in an interferometer. The resulting fringe pattern was physically displaced by the rotation of the earth, as measured against a reference fringe pattern. The displacement agreed with the calculated values within the observational accuracy.

The laser gyro uses the same basic techniques with several apparent differences:

- Instead of conventional light, a laser beam is used.
- Instead of measuring a minute displacement of a fringe pattern, frequency differences are measured between the cw and ccw laser beams.
- Instead of a rectangle with a 6000-foot perimeter, a triangular path length of 12.6 inches is employed.
- Instead of sewer pipe, a solid block of quartz serves as a stable, rugged casing.

Consider the two counter-rotating cw and ccw laser beams propagating around the triangular "lasing" path. When the cavity has zero rotation rate about the input axis, the frequency and wavelength of both beams are identical. Pick a reference position anywhere on the lasing triangle and consider the effect of cw rotation on the cavity length. As the cavity rotates in the cw direction, the cw beam sees an apparent lengthening of the path length while the ccw sees an apparent shortening of the path length (crudely analogous to the Doppler effect on sound).

Since only an integral number of wavelengths exists in the cavity, in a rotating ring, the wavelength of the ccw beam decreases, and the wavelength of the cw beam increases. Correspondingly, the frequency of the cw beam decreases and that of the ccw beam increases by equal amounts.

Therefore, angular rotation of the laser cavity results in a frequency split of the two laser beams which is proportional to the angular rate. The equation for this frequency split is

$$\Delta f = \frac{4A}{L\lambda} \Omega = K \Omega$$

where

A = enclosed area of laser triangle

L = path length of cavity

λ = wavelength of the laser light

Ω = rotation rate about the input axis

K = scale factor

For the LARS gyros

L = 12. 6 inches

K = 1 cycle/3. 8 arc seconds

In summary, in the gas ring laser gyro, there are two counter-rotating laser beams, cw and ccw. When the gyro is motionless, the frequencies of both beams are identical although they are independent oscillators (lasers). When the laser triangle rotates about an axis perpendicular to the plane of the triangle, a frequency split occurs between the two lasers which is proportional to the angular rotation rate.

In order to implement this effect to sense rotational inputs, three elements must be combined: (1) An active gas medium which supplies gain to the laser beam; (2) a resonant cavity with low-loss reflectors to provide positive feedback by reflecting the beam into the active gas medium; and (3) a readout scheme which senses the resulting frequency split.

ELEMENT 1 - THE ACTIVE GAIN MEDIUM

The schematic of Honeywell's triangular ring laser, (Figure A1), illustrates how the three elements are combined. For the first element, a d-c voltage near 1000 volts is applied at anodes one and two, and some of the gas in the cavity ionizes to become a current flow path between the anodes and the cathode. The ionized gas medium is composed of free electrons, gas ions, and energetic helium and neon atoms, where the electrons are accelerated to the anodes, and the positive gas ions are accelerated to the

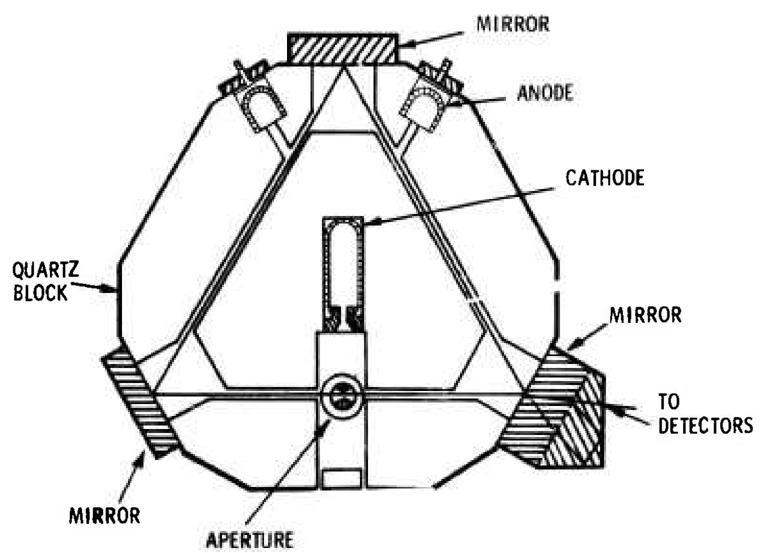

Figure A1. Laser Gyro

cathode. In the gas laser vocabulary a gas discharge is set up between each anode and the cathode which, in a helium-neon gas discharge, liberates visible light much like a neon sign with an orange color characteristic of the neon gas. The cavity or tube enclosing the gas is designed to align the discharge paths coincident with the laser beam.

This gas discharge is the gain medium, as it is capable of liberating light photons to the laser beam, thereby giving the laser beam power gain.

ELEMENT 2 - THE RESONANT CAVITY

As shown in Figure A1, as an incident beam strikes a dielectric mirror it is reflected into the next leg of the triangle, which is also part of the gas discharge or gain medium. Moreover, the three mirrors defining the light resonant cavity are aligned so that the laser beam is always fed back into the gain medium (positive feedback). Note that the conditions for oscillation are familiar -- that is, positive feedback and gain greater than unity. Thus, in reality the ring laser is a continuous wave light oscillator that resonates at light frequencies (near 10^{14} Hz) in the resonant cavity defined by the three mirrors.

For the laser beam to exist, the light energy gain the beam achieves as it traverses one round-trip of the triangular cavity must be greater than the light energy lost due to light transmission (leakage) at the three mirrors plus other smaller losses. The steady-state power in the beam depends on the magnitude of the gain and the losses of the laser cavity.

The laser light has several unique features when compared with light from any other source. Laser light from the gyro is plane-polarized, extremely well collimated, and highly coherent. In simpler terms, respectively, the electric field vector along the laser wave front is aligned, the beam does not disperse appreciably over distance, and the spectral bandwidth is typically less than 10 KHz. (The laser light frequency is on the order of 10^{14} Hz.) Power output from a typical Honeywell laser gyro is roughly one milliwatt from each beam.

The lasing material must be capable of true continuous operation. It must also be nearly perfect optically; i.e., a gas. This fixes the wavelength used to one of those available in a gas laser gain medium. This choice is made on the basis of available gas transitions at visible, or nearly visible wavelengths. The only medium suitable for high-performance laser gyro work is Ne with He. In the HeNe laser, two wavelengths may be chosen: 1.15μ, or 0.633μ transitions. For the LARS design, the 1.15μ transition was used.

ELEMENT 3 - THE READOUT SCHEME

A typical mechanization of the laser gyro readout at Honeywell is shown in Figure A2. A readout prism (Figures A1 and A2) attached at one of the cavity defining mirrors is designed to combine the transmitted laser beams in order to obtain a fringe pattern.* The fringe spacing is a function of the roof angle of the readout prism (see Figure A2) and the fringes are motionless when there is no rotation about the gyro input axis.

The previously described frequency split causes the fringe pattern to have an apparent transverse motion, the velocity of which is proportional to the rotation rate about the input axis. Two light-sensitive photo diodes are positioned at the fringe pattern (see Figure A2) to sense the fringe pattern motion. Although only one sensor is necessary to sense and read out rotation rate, two photo diodes are used and placed in a particular dimensional relationship as a function of a fringe spacing. The subsequent readout electronics are designed to process the sensor outputs to give both rotation rate and rotation direction (cw or ccw) information.

In summary, at one gyro corner mirror, the leakage light from both laser beams (cw and ccw beams) is optically combined to produce a motionless fringe pattern. When a rotation input about the input axis occurs, the fringe pattern traverses two photo diodes at a rate proportional to the gyro rotation rate. Finally, the photo diode outputs are processed electronically to produce rotation rate and direction information in the form of two electronic pulse outputs.

BASIC ERROR SOURCES

Although the laser gyro is not perfect it possesses several factors which must be controlled if the laser gyro is to be a satisfactory sensing instrument for this application. The gyro operates by sensing the relative frequency differences between two lasers occupying the same physical cavity and traveling in opposite directions. Therefore, any factor that can cause changes in th the apparent length difference of the two cavities, other than inertial input rate, will introduce errors into the laser gyro output. From a practical standpoint, only two parameters, lock-in and null shift, affect the performance characteristics of the gyro.

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*The fringe pattern is alternate bright and dark areas due to constructive and destructive interference of the optically mixed light beams. In laser vocabulary, the beams are optically heterodyned to form a fringe pattern.

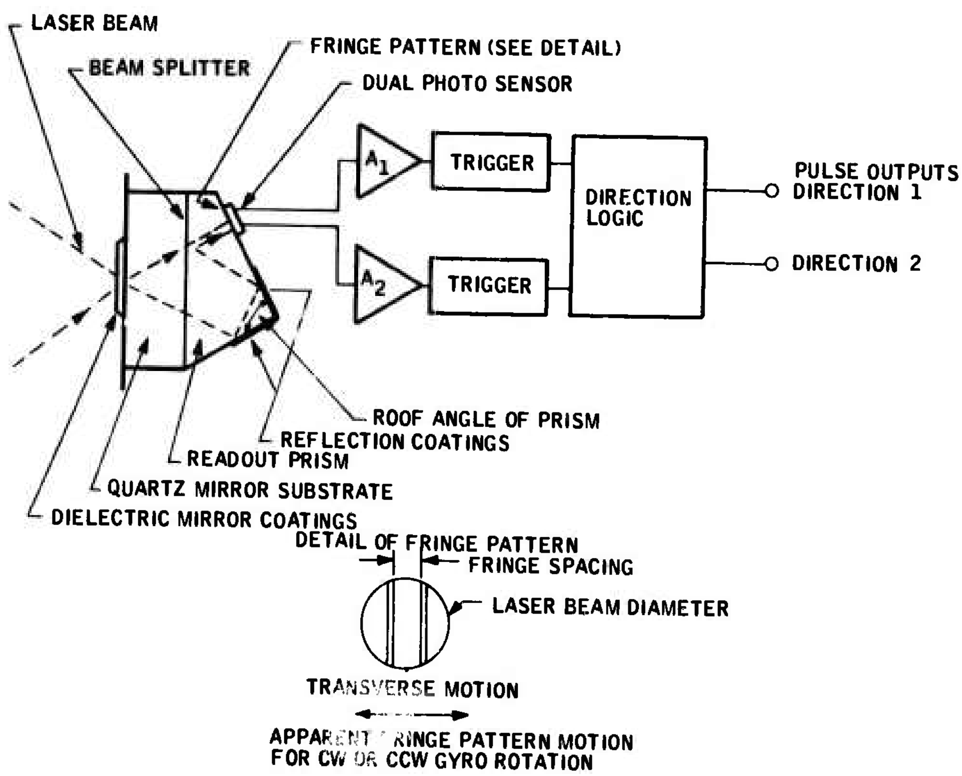


Figure A2. Laser Gyro Readout Mechanization

Lock-In

Lock-in is a phenomenon which arises from coupling between the two laser oscillators. Lock-in in a laser gyro was initially observed in early 1963 and has been observed for many decades in coupled electrical oscillators.

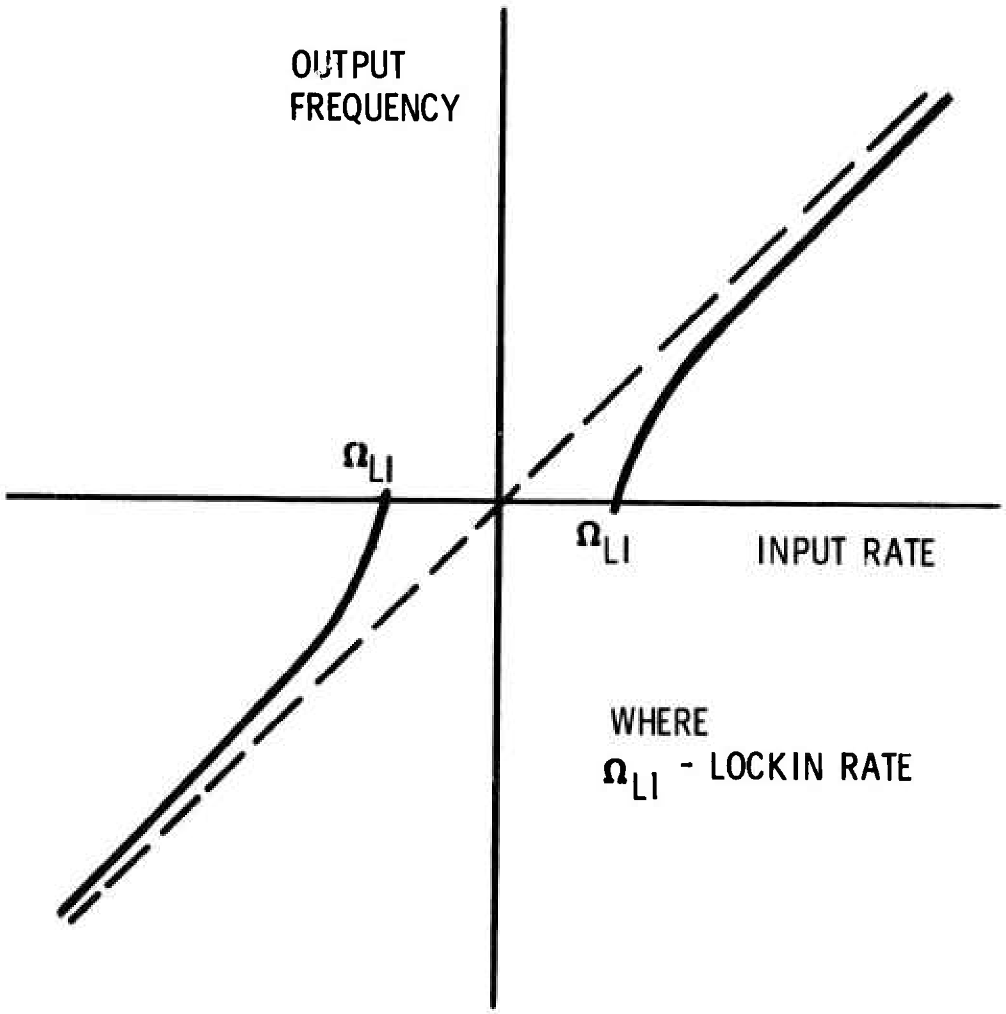
When the output of the laser gyro is observed as a function of the rotation rate, the difference frequency is proportional to the input at high rates. However, as the input rate is reduced, the frequency difference between the two oscillators will fall to zero before the input rate goes to zero. This is apparent from the fact that the output fringe pattern does not move. The input rate at which this lock-in zero-difference frequency occurs, is called the lock-in rate. In practice the magnitude of the lock-in rate for a 12.6-inch path length gyro operating at 1.15μ is one to two degrees per second. A typical input-output curve depicting this effect is shown in Figure A3. A more thorough discussion of lock-in theory is presented in Section II of Volume II.

Null Shifts

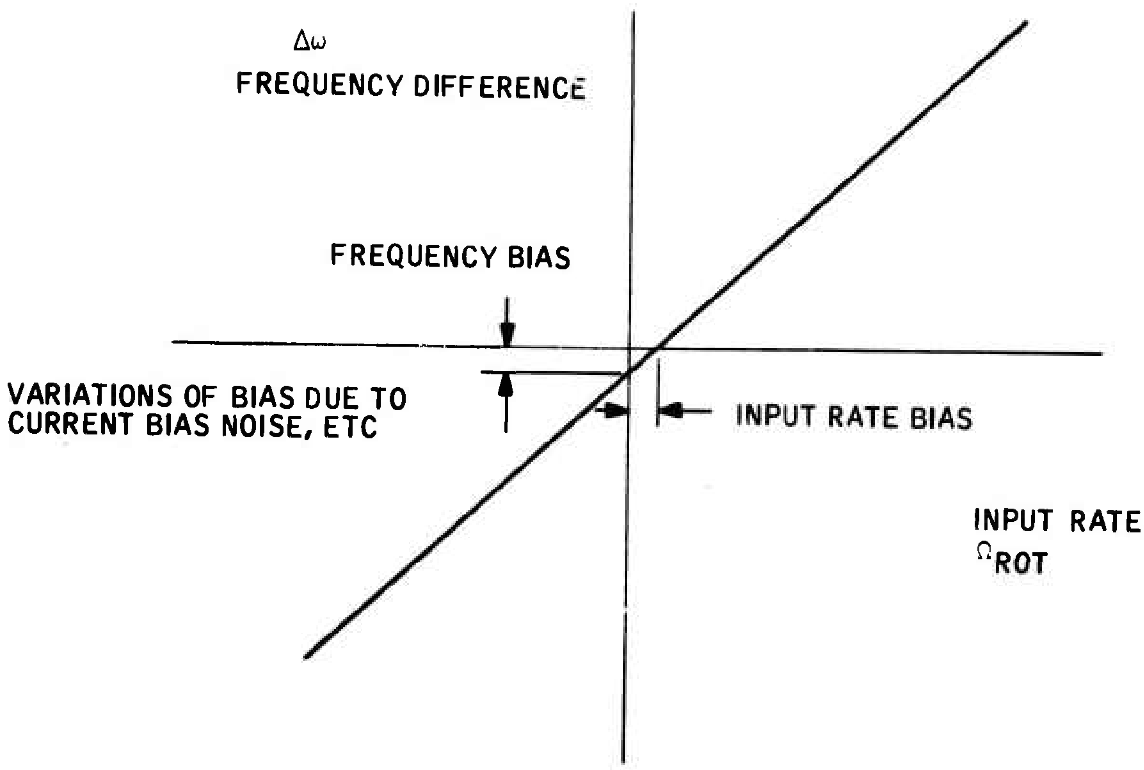
A second source of errors is the null shift, equivalent to a fixed bias torque in a conventional gyro, which arises from the direct current used to excite the laser gyro. Null shifts resulting from this parameter must be considered and reduced. When a gas discharge is sustained with a direct current the gas flows in the discharge cavity. This flow produces a shift in the index of refraction that depends upon the relative directions of the laser energy and the gas flow. Therefore, the cavity will appear longer in one direction than the other, and will cause an apparent null shift in the input rate sensed by the gyro. Balancing of the currents from the two anodes balances the resulting gas flow, thereby cancelling the null shifts due to this effect. This effect is used to advantage in the "current dither" form of lock-in compensation as will be discussed later. A typical input-output curve depicting this effect is shown in Figure A4. A more thorough discussion of null offset theory is presented in Section II of Volume II.

LOCK-IN COMPENSATION

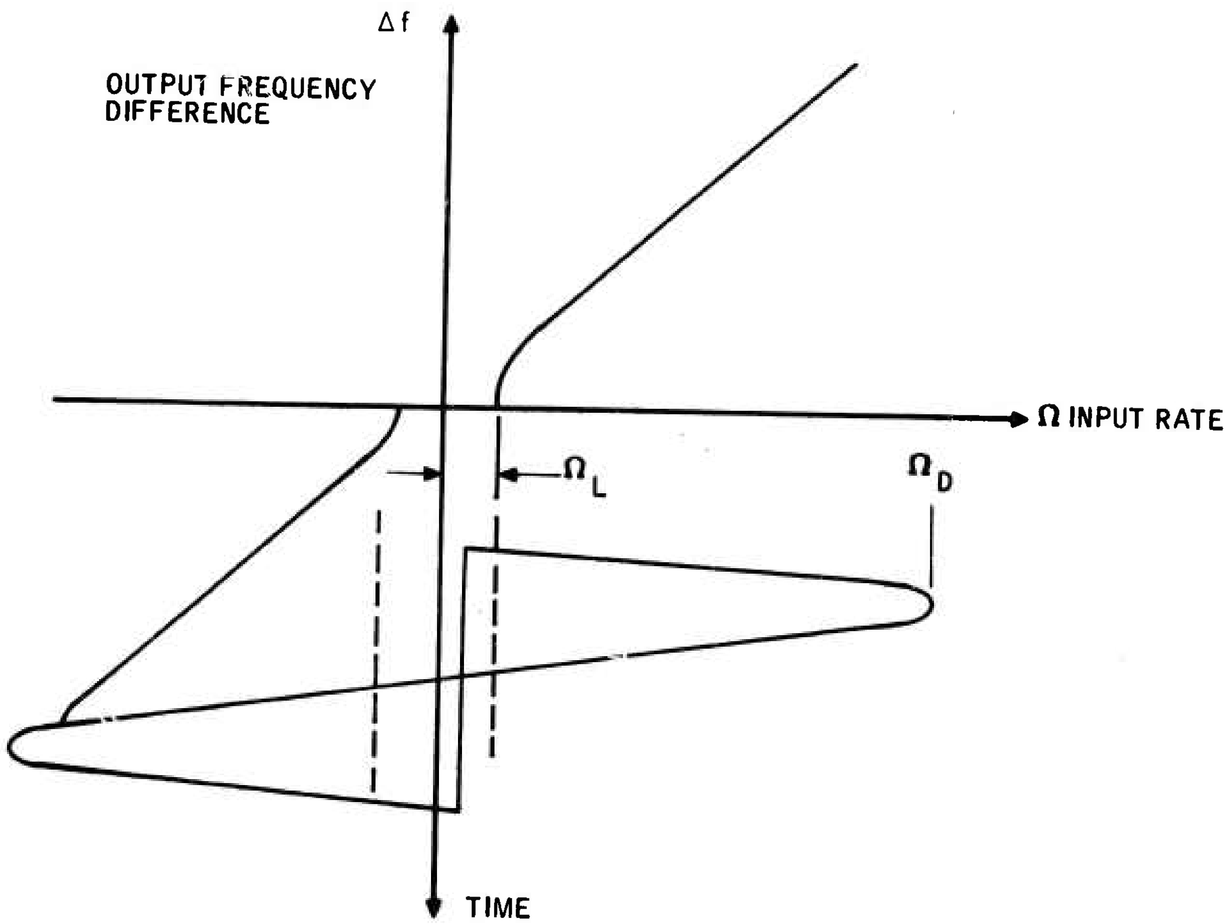
The lock-in phenomena prevents the laser gyro from accurately measuring low input rates unless some means is provided to overcome this effect. One technique is to introduce a known input rate into the gyro. If that known input rate is a sinusoidal dither as shown in Figure A5, then the effective input rate normally seen by the gyro is in excess of the lock-in value. Since the laser gyro is an integrating-rate gyro, the sinusoidal portion of the total input angle will integrate to zero leaving a net angle proportional to the true input rate. The accuracy of this form of compensation is obviously related



A3. Uncompensated Ring Laser Input-Output Relationship



A4. Null Shift Effects

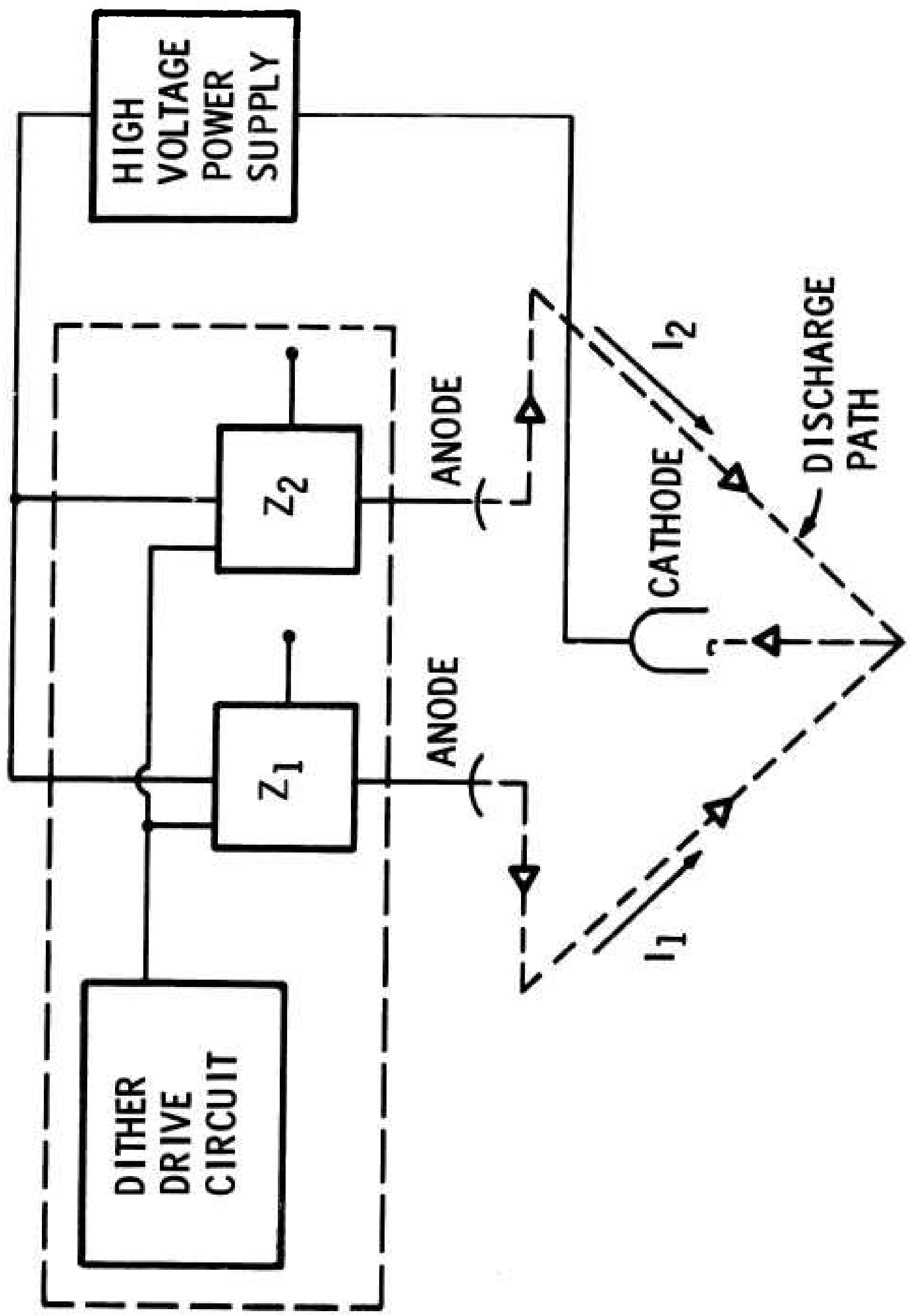


A5. Lock-in Compensation

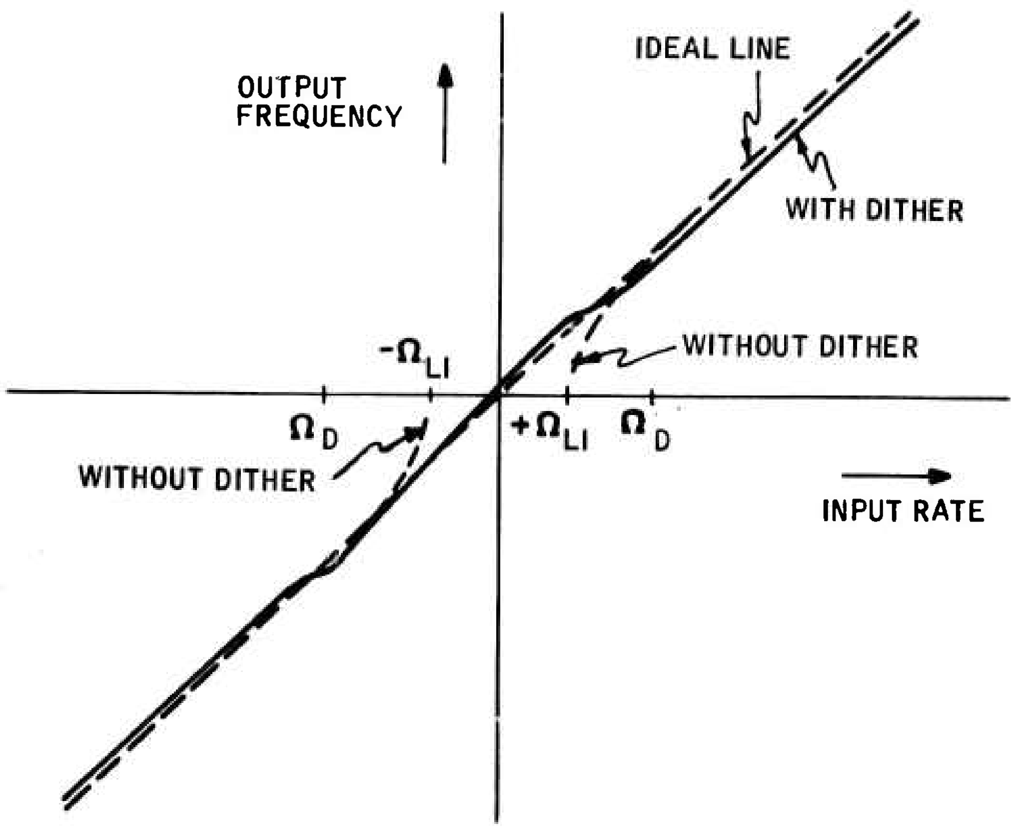
to such items as the frequency and amplitude of the dither and the integration or sampling time.

In order to meet the threshold requirement, the LARS design required some form of compensation to overcome the natural lock-in of the gyro. After completing a tradeoff study early in the program, a decision was made to develop a "current dither" compensation technique for the LARS application. This technique utilizes the frequency splitting attained by relative gas flow described under Null Shifts. The gas flow is a direct function of the discharge current, and hence the frequency split is proportional to the current difference between the two discharge legs. In the LARS design, the discharge current consists of two components, a constant d-c level and a time dependent level. This is accomplished by varying line impedances external to the discharge as shown in the schematic of Figure A6. The resulting "dithered" gas flow produces alternating input rates which integrate to zero but allows the LARS to sense low input rates to the required accuracy.

A thorough discussion of the compensation technique and the impact of these parameters is also presented in Section II of Volume II. In summary, with the dither applied the input-putput relationship of the laser gyro is continuous and essentially linear as shown in Figure A7.



A6. Schematic of One Axis of Current Dither Compensation Circuit



A7. Input-Output with Dither

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13. ABSTRACT

This summary volume is Volume I of three volumes which make up the Final Technical report for the Laser Angular Rate Sensor (LARS) program. The program was sponsored by the Advanced Research Projects Agency and was contracted and administered by the Army Missile Command. The purpose of the program was to develop and qualify a rate sensor for anti-ballistic missile applications. Following an extensive developmental phase, two flight-weight LARS units were fabricated and subjected to a thorough range of performance and environmental tests. The environmental tests were extremely severe, taxing the capability of state-of-the-art test facilities. Program results were very encouraging in all aspects. Performance goals were met or exceeded in seven of eight key areas. The reaction time goal was not met, but the technology is now available to provide the very fast reaction time characteristics desired. Environmental goals were met or exceeded in five of the seven major environments. In the two areas -- temperature range and random vibration -- the technology is also now available to meet the program objectives.

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